LOW POLARISATION MODE DISPERSION (PMD) OPTICAL FIBER LINK, AND METHOD OF MAKING THE SAME

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DESCRIPTION

The present invention generally relates to the field of optical fibers and to manufacturing methods thereof. More particularly, the invention concerns an optical fiber link featuring a low Polarization Mode Dispersion (shortly, PMD), and a method of realizing it.

Optical signals transmitted through single-mode optical fibers comprise two orthogonal polarization modes (typically denoted Transverse Electric, or TE, and Transverse Magnetic, or TM). In case the fiber has a perfectly cylindrical core of uniform diameter, the two modes TE and TM propagate at a common velocity. However, in real optical fibers the cylindrical symmetry of the core may be disrupted due to shape defects or non-uniform stresses. As a result, a phase difference can accumulate between the two modes as they propagate, and the fiber is said to exhibit "birefringence". In particular, the birefringence introduced by shape and stress asymmetry is known as "intrinsic linear birefringence".

The structural and geometrical irregularities of the optical fiber that give rise to birefringence typically originate from the fiber preform itself, and are modified during the process of drawing the fiber. This process is usually carried out by means of an apparatus known as a "drawing tower", starting from a glass preform. In practice, after the preform has been placed in vertical position and heated to a temperature above the softening point within a suitable furnace, the molten material is drawn downwards at a controlled velocity in such a way as to produce a threadlike element that forms the optical fiber itself. In this process, asymmetrical stresses are typically applied to

the fiber.

In a birefringent fiber, the two components TE and TM of the fundamental optical mode, initially in phase with each other, return to be in phase again only after a certain propagation length, commonly known as the "beat length" (L_B). In other words, the beat length is the period of repetition of a certain state of polarization (on the assumption that the fiber maintains a constant birefringence over this length). A further characteristic parameter of a birefringent fiber is the "correlation length" (L_F), which is defined as the distance over which the autocorrelation function of the birefringence is $1/e$ times its maximum value.

In the so-called "polarization-preserving" optical fibers, asymmetry is deliberately introduced into the fiber to generate birefringence. However, in ordinary (*i.e.*, non-polarization-preserving) fibers, birefringence is detrimental to the fiber performance.

In fact, when pulsed signals are transmitted into an optical fiber, birefringence is a cause of pulse spreading, since the two polarization components, TE and TM, travel at different group velocities (*i.e.* become dispersed). This phenomenon, known as Polarization Mode Dispersion (PMD), has been widely studied in recent years because of its importance in periodically amplified light guide systems.

Typically, the phenomenon of PMD leads to a limitation of the width of the signal transmission band and, consequently, a degradation of the performance of the optical fibers along which the aforesaid signals are transmitted. This phenomenon is therefore undesirable in systems of signal transmission along optical fibers, especially in those operating over long distances, in which it is necessary to minimize any form of attenuation or

dispersion of the signals to guarantee high performances in transmission and reception.

U.K. patent application GB-A-2101762 considers the effects on PMD of post-draw fiber twisting and observes that, although such twisting reduces the PMD resulting from intrinsic linear birefringence, it introduces torsional stresses that generate a substantial circular birefringence due to the photo-elastic effect. Twisting a drawn fiber thus reduces the bandwidth limitation due to one effect, whilst replacing it with another. The same patent application thus proposes to spin the preform during drawing, so that twisting can be effected whilst keeping the fiber material substantially unstressed. Spinning is performed at a relatively high rate, so that its spatial repetition frequency, or spin pitch, is small compared to the beat length due to intrinsic birefringence; as a result, an optical fiber can be produced wherein the contribution of birefringence due to form and stress asymmetries is greatly reduced. Such a fiber is termed "spun" fiber, to distinguish it from a (post-drawn) twisted fiber. Conveniently, the preform is spun at a substantially constant rate, but it could even reverse in direction, oscillating from a right-handed to a left-handed twist.

In the present description, the same distinction as above will be made between "spin" and "twist". More precisely, the terms "spin" and "twist" are herein used to identify two different types of torsion of the fiber: "spin" identifies a torsion that is frozen-in during drawing, being applied to a viscous portion of the fiber and kept as a structural modification of the fiber while cooling; differently, "twist" identifies an elastic torsion of the fiber, which is present when a torque is applied to a portion of fiber whose ends are constrained against

rotation. In other words, although both spin and twist alter the fiber in shape, so that parts previously in the same straight line are located in a spiral curve, a twisted fiber will rotate back to its original shape when its ends are released from the rotation constraint, while a spun fiber will keep this alteration as an intrinsic and permanent deformation. Due to spinning, the fiber undergoes a rotation of its polarization axes. As a result, when optical pulses are transmitted into the optical fiber, they propagate alternately on the slow and fast birefringence axes, thus compensating the relative delay and reducing the pulse spreading. This is equivalent to having a local effective refractive index for the optical pulses equal to the mean refractive index on the two axes, the average being taken over the pulse length along the fiber.

Theoretical studies have shown that the dominant process for the reduction of PMD in a spun fiber is the averaging of the local fiber anisotropy by the rapid procession of the axes of asymmetry along the fiber.

The United States patent US 4,504,300, relating to a technique for making an optical fiber having chiralic structure, addresses drawbacks related to preform rotation and proposes a new spinning technique, consisting in rotating the fiber instead of the preform. In particular, a device is disclosed comprising means disposed just below the preform for twisting the fiber during fiber drawing. The twisting means comprise a rotating hoop supporting three pulleys. The twisted fiber is coated by coating means, followed by cooling by fast-cooling means that facilitate freezing-in of the twist.

The United States patent US 5,418,881 proposes to arrange the device adapted to apply the torque to the fiber downstream of the coating station, so as to avoid damaging

the fiber surface. In particular, the torque is applied by alternately canting in clockwise and counterclockwise direction a fiber-guiding roll having a rotation axis which extends perpendicularly to the drawing axis of the fiber. In this way, in at least a portion of the fiber the spin impressed to the fiber is alternately clockwise and counter-clockwise. The same patent states that applying a clockwise and a counterclockwise torque to the fiber substantially prevents introduction of an elastic twist to the fiber.

The United States patent application N. US2001/0020374 proposes a new device that overcomes some drawbacks of the canting-roll technique and allows both unidirectional and alternate spinning, but also states that alternate spinning is to be considered as preferable since it prevents the presence of residual torsions (*i.e.*, of a residual twist) on the fibers wound onto the collecting spool, thus making easier both the unwinding and wiring operations of the same.

In the United States patent US 5,943,466, it is proposed to spin the fiber during drawing in accordance with spin functions which are not substantially constant (in the sense that they change substantially as a function of distance along the length of a fiber or as a function of time), not substantially sinusoidal, and have sufficient variability (*e.g.* sufficient harmonic content) to provide a substantial reduction in PMD for a plurality of beat lengths.

The Applicant has found some other drawbacks of the alternate spinning technique, not previously highlighted. Alternate spinning may for example cause a relatively low mechanical efficiency of the spinning device, due to the continuous accelerations and decelerations. Moreover, with respect to a unidirectional spin, an alternate spin requires a relatively high peak profile amplitude to compensate those

positions of the profile where the rotation slows down to change direction and, therefore, to guarantee a sufficient average spin rate. Besides all this, the sites where the spin rate is zero are detrimental for the PMD, because there is an increase of the effective birefringence seen by the pulse, and so a higher contribution for PMD.

The paper by A. Galtarossa *et al.*, "PMD statistical properties of constantly-spun fibers", ECOC-IOOC 2003 Proceedings, Vol. 4, Th. 1.7.4, and the paper by A. Galtarossa *et al.* "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003, pp. 1639-1641 report the PMD induced delay (*i.e.* the mode delay - in ps - induced by PMD or, equivalently, the mean fiber Differential Group Delay, or "DGD") of unidirectionally-spun fibers. It can be shown that, while in an unspun fiber or an alternately spun fiber the PMD induced delay increases proportionally to the square root of the fiber length, in a unidirectionally-spun fiber the PMD induced delay has a higher increase rate, and only asymptotically increases proportionally to the square root of length. In particular, the PMD induced delay in a unidirectionally-spun fiber asymptotically increases at the same rate as the PMD induced delay of an unspun fiber having the same beat length L_B and the same correlation length L_F. Advantageously, a PMD coefficient, hereinafter indicated with PMD_C, defined as the mean fiber DGD divided by the square root of length, is introduced. For unspun or alternately spun fibers, this parameter is independent from the fiber length.

In greater detail, reference is made to **Figure 1**, wherein a theoretical diagram of the average of the squared DGD $<\Delta\tau^2>$ (in ordinate, unit ps^2) as a function of the propagation distance (in abscissa, unit km) is shown for an

unspun fiber (curve (a)) with a typical (constant) PMD_c (*e.g.*, 0.1 $ps/km^{1/2}$), an alternately spun fiber (curve (b)) with a typical (constant) PMD_c (*e.g.*, 0.04 $ps/km^{1/2}$) and a unidirectionally spun fiber (curve (c)) with the same beat length L_B and the same correlation length L_F as the unspun fiber. From the diagram, it can be appreciated that the slope of curve (c) (*i.e.* the increase rate of $<\Delta\tau^2>$) is not constant, but increases with the propagation distance up to a constant value corresponding to the slope of curve (a). The length over which the slope changes can be denoted as a transient length. Since the PMD_c is proportional to the square root of $<\Delta\tau^2>$ divided by the square root of the fiber length, it is expected that such a coefficient increases with the propagation distance (*i.e.* with the fiber length), differently from the PMD_c of unspun and alternately spun fibers, which is constant. In particular, for the unidirectionally spun fiber, the increase of the PMD_c will be more rapid in the initial transient, before the increase rate of the PMDc becomes similar to that of the unspun fiber; after the transitory, the PMD_c increases very slowly reaching asymptotically the PMD_c of the unspun fiber. As already predicted in the article by Galtarossa *et al.*, "Optimized Spinning Design for Low PMD Fibers: An Analytical Approach" Journal of Lightwave technology vol. 19 no.10 Oct. 2001 pp. 1502-1512, the initial PMD_c increase is the one predicted in the deterministic regime.

In the above-cited articles by Galtarossa, it is also described that the magnitude of the spin period changes the length of the above-mentioned transient regime, and that a transient characteristic length L_T can be defined for unidirectionally spun fibers (curve (c) in **Figure 1**):

$$L_T = L_F\left(1+\frac{4L_B^2}{p^2}\right)$$

where p is the spinning period, L_F the correlation length and L_B the beat length. The transient characteristic length L_T is equal to the intercept of the linear asymptotic behavior of curve (c) with the abscissa axis. The propagation distance (or length of fiber span) required to approach the regime PMD behavior of the unspun fiber is estimated to be of some transient characteristic lengths.

Assuming that the parameters appearing in the above formula fall within the typical ranges: $L_F = 1 \div 20$ m, $L_B = 5 \div 15$ m, and $p = 0.1 \div 1$ m, the transient characteristic length L_T may vary between 0.1 and 1,800 km, covering four orders of magnitude. If the transient characteristic length L_T is much greater than the link length, the PMD_c increase remains moderate. On the contrary, when the transient characteristic length L_T is comparable to or smaller than the link length, the PMD_c increase over the link becomes significant and can be detrimental to signal transmission.

Thus, unidirectionally spun fibers with short transient characteristic lengths suffer from a growth of the PMDc with the fiber length, which cancel the advantage of using a spun fiber.

Another prediction made in the cited paper by A. Galtarossa published in Optics Letter is that the DGD statistical distribution for short enough unidirectionally spun fibers may deviate from the typical Maxwell distribution exhibited by both unspun and alternately spun fibers.

In view of the state of the art outlined in the foregoing, it appears that an optimum solution to the problem of PMD in fibers does not exist: unspun fibers have in fact a PMD which, for several applications, is too high; on the other hand, alternately spun fibers exhibit the series of problems previously mentioned. From the above

theoretical considerations it also comes out that unidirectionally spun fiber may be preferable with respect to unspun fibers only for relatively short fiber lengths, because they experience a growth of their PMD_c as the length increases, which becomes asymptotically equal to the one of unspun fibers.

Thus, it has been an object of the present invention to devise a solution to these problems.

In particular, it has been an object of the present invention to provide an optical fiber link, and a method of realizing it, featuring a significant limitation of the PMD_c increase with fiber length.

With these objects in mind, the Applicant has found that the increase in the PMD_c exhibited by unidirectionally spun fibers can be completely eliminated or substantially reduced if an optical fiber link is made of unidirectionally spun fiber spans, of appropriate lengths, with opposite helicity, spliced one to the other to form the optical fiber. With "helicity", it is here intended the fiber spin direction, which can be either right-handed or left-handed (*i.e.* clockwise or counter clockwise).

Therefore, an optical fiber link according to the present invention includes at least a first and a second optical fiber spans unidirectionally-spun in opposite directions and joined to each other. Preferably, the optical fiber link comprises a first type of fibers unidirectionally-spun in a first direction, and a second type of fibers unidirectionally-spun in the opposite direction, the fibers of the first type being alternated to the fibers of the second type, *i.e.* fiber spans of opposite helicity are alternated to each other.

According to an aspect of the present invention, an optical fiber link is provided for, as set forth in appended

independent optical fiber link claim 1.

In brief, the optical fiber link comprises a plurality of optical fiber spans, joined one to the other, said plurality of optical fiber spans including at least one first unidirectionally-spun optical fiber span and at least one second unidirectionally-spun optical fiber span having mutually opposite spinning directions.

For the purposes of the present invention, the terms "spin", "spinning" and "spun" all relate to a torsion that is frozen-in during drawing, being applied to a viscous portion of the fiber and kept as a structural modification of the fiber while cooling. In other words, a spun fiber will keep this alteration as an intrinsic and permanent deformation.

Also, for the purposes of the present invention, with "unidirectional spin" it is intended a spin that occurs on a same direction apart from possible local inversions, for example due to fiber slippage in the spinning device or in the traction device.

Preferably, the unidirectional spin here considered is constant, but it may also derive from the superposition of a constant spin function and a variable spin function, the variable spin function having preferably small amplitude and long period.

Preferably, the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span are joined to each other.

In a preferred embodiment of the present invention, the plurality of optical fiber spans includes a plurality of first optical fiber spans, and a plurality of second optical fiber spans, the first optical fiber spans and the second optical fiber spans being spans of unidirectionally spun optical fibers having mutually opposite spinning directions.

The first optical fiber spans and the second optical fiber spans are alternated to each other in the optical fiber link.

The first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span may have substantially a same span length.

Defined a spinning period p, a correlation length L_F and a beat length L_B for the fiber, the length of the first unidirectionally-spun optical fiber span and/or of the second unidirectionally-spun optical fiber span is preferably lower than 10 times the transient characteristic length L_T defined as

$$L_T = L_F\left(1+\frac{4L_B^2}{p^2}\right).$$

More preferably, said span length is lower than 5 times the transient characteristic length L_T.

In an embodiment of the present invention, said span length is equal to or lower than approximately 3 Km, preferably equal to or lower than approximately 1 Km.

In particular, the first unidirectionally-spun optical fiber span and the second unidirectionally-spun optical fiber span may have substantially a same spin rate.

Preferably, the number of first optical fiber spans and second optical fiber spans is odd.

According to another aspect of the present invention, an optical cable line as set forth in appended claim 10 is provided.

Summarizing, the optical cable line includes a plurality of optical cable trunks joined to each other. Said plurality of optical cable trunks comprises at least a first optical cable trunk and a second optical cable trunk, the first optical cable trunk including a first optical fiber span unidirectionally-spun in a first direction, and the

second optical cable trunk including a second optical fiber span unidirectionally-spun in a second direction opposite to the first direction, the first and the second optical fiber spans being optically linked to each other.

In particular, the first and the second optical fiber spans are joined to each other.

The first and the second optical fiber spans may have substantially a same span length.

Preferably, the span length of the first and/or of the second optical fiber span is lower than 10 times the transient characteristic length L_T defined above, more preferably lower than 5 times the transient characteristic length L_T. In particular, the fiber span is preferably equal to or lower than approximately 3 Km, more preferably equal to or lower than approximately 1 Km.

In particular, the first and the second optical fiber spans may have substantially a same spin rate.

According to an embodiment of the present invention, the plurality of optical cable trunks include a plurality of first optical fiber spans, and a plurality of second optical fiber spans joined to each other to form an optical fiber link, the first optical fiber spans and the second optical fiber spans being unidirectionally-spun optical fibers having mutually opposite spin directions, and the first optical fiber spans and the second optical fiber spans being alternated to each other in the optical fiber link.

In particular, in an embodiment of the present invention at least one optical cable trunk of said plurality of optical cable trunks has an optical core including a plurality of unidirectionally-spun optical fiber spans having a same spin direction.

In another embodiment of the invention, at least one optical cable trunk of said plurality of optical cable

trunks has an optical core including at least two unidirectionally-spun optical fiber spans having opposite spin directions.

Preferably, the total number of optical cable trunks is odd.

According to still another aspect of the present invention, a method of realizing an optical fiber link as set forth in appended independent method claim 21 is provided.

The method comprises:

providing at least a first span of optical fiber, unidirectionally-spun in a first direction;

providing at least a second span of optical fiber, unidirectionally-spun in a second direction opposite to the first direction; and

joining the first span and the second span together at a respective end thereof.

According to a further aspect of the present invention, a method of producing an optical cable as set forth in appended claim 22 is provided.

The method comprises providing a plurality of optical fibers to a cable manufacturing line, wherein said plurality of optical fibers comprises at least a first optical fiber being unidirectionally-spun in a first direction, and at least a second optical fiber being unidirectionally-spun in a second direction opposite to the first direction.

According to a still further aspect of the present invention, a method of realizing an optical cable line as set forth in appended claim 23 is provided.

The method comprises forming a plurality of optical cable trunks, each one including at least one optical fiber span, and joining the optical cable trunks one to another.

The step of forming a plurality of optical cable trunks

comprises forming at least one first trunk including a first optical fiber span unidirectionally-spun in a first direction, and forming at least one second trunk including a second optical fiber span unidirectionally-spun in a second direction opposite to the first direction; said joining the optical cable trunks one to another includes optically linking the first optical fiber span to said second optical fiber span.

These and other features and advantages of the present invention will be made apparent by the following detailed description of an embodiment thereof, provided merely by way of non-limitative example, description that will be conducted making reference to the attached drawings, wherein:

Figure 1 is a diagram showing the predicted variation of the average of the squared Differential Group Delay (DGD) (in ordinate) with the propagation distance (in abscissa) for: an unspun fiber (curve (a)), an alternately spun fiber (curve (b)) and a unidirectionally spun fiber (curve (c)) with the same beat length L_B and the same correlation length L_F as the unspun fiber;

Figure 2 schematically shows a portion of an optical fiber link according to an embodiment of the present invention, comprising alternated, unidirectionally spun fiber spans having mutually opposite helicity;

Figures 3A and **3B** show diagrams of the predicted variation of the PMD_c (in ordinate, unit ps/km$^{1/2}$) with the propagation distance (in abscissa, unit km) for the fiber of **Figure 2** for various lengths of the alternated fiber spans, and for two different values of the fiber transition characteristic length;

Figure 4A shows in transverse section an optical cable containing optical fibers in accordance to an embodiment of

the present invention;

Figure 4B schematically shows in lateral view a portion of an optical cable line in accordance with the present invention;

Figure 5 is a diagram showing the predicted variation with the propagation length (in abscissa, unit km) of the ratio between the average of the squared DGD values to the square of the averaged DGD values (in ordinate) for a fiber with the same parameters of **Figure 3A**, with alternated spans length of 5 km;

Figures 6A to **6F** are diagrams showing the statistical distribution of the DGD values for the same fiber of **Figure 5** at propagation distances indicated in **Figure 5** with the letters a) to f) respectively;

Figure 7 shows a drawing tower adapted to drawing unidirectionally spun fibers;

Figure 8 illustrates a spinning device suitable to be used in the drawing tower of **Figure 7**;

Figure 9 shows a twist apparatus suitable to be used in the drawing tower of **Figure 7**;

Figure 10 illustrates a re-spooling apparatus;

Figure 11 shows a twist apparatus to be used in the drawing tower of **Figure 7**, in alternative to the apparatus of **Figure 9**; and

Figures 12 and **13A** to **13D** are diagrams showing the results of experiments conducted by the Applicant.

With reference to the drawings, in **Figure 2** a portion of an optical fiber link according to an embodiment of the present invention is shown very schematically.

By optical fiber link there is intended an optical fiber made up of two or more optical fiber spans, joined to each other.

The optical fiber link, indicated globally as **300**, is

for example of the type used in optical fiber cables for optical communication systems.

The optical fiber link **300** (the portion of which shown in **Figure 2** being for example an intermediate portion along the overall length of the optical fiber link) comprises a plurality of optical fiber segments or spans ..., $\mathbf{305}_{(k-1)}$, $\mathbf{305}_{k}$, $\mathbf{305}_{(k+1)}$, $\mathbf{305}_{(k+2)}$, $\mathbf{305}_{(k+3)}$ $\mathbf{305}_{(k+4)}$, $\mathbf{305}_{(k+5)}$, $\mathbf{305}_{(k+6)}$, ..., of shorter length, joined one to another at respective free ends to form the optical fiber link **300**; in jargon, the operation of joining of two optical fiber segments together is referred to as "splicing"; in the drawing, the points where two generic optical fiber spans ..., $\mathbf{305}_{(k-1)}$, $\mathbf{305}_{k}$, $\mathbf{305}_{(k+1)}$, $\mathbf{305}_{(k+2)}$, $\mathbf{305}_{(k+3)}$ $\mathbf{305}_{(k+4)}$, $\mathbf{305}_{(k+5)}$, $\mathbf{305}_{(k+6)}$, ..., are spliced together are schematically indicated by **310**.

According to an embodiment of the present invention, the optical fiber spans ..., $\mathbf{305}_{(k-1)}$, $\mathbf{305}_{k}$, $\mathbf{305}_{(k+1)}$, $\mathbf{305}_{(k+2)}$, $\mathbf{305}_{(k+3)}$ $\mathbf{305}_{(k+4)}$, $\mathbf{305}_{(k+5)}$, $\mathbf{305}_{(k+6)}$, ..., are segments or spans of unidirectionally spun optical fibers. In particular, spans of unidirectionally spun optical fibers with mutually opposite spinning helicity (right-hand, or σ_+, helicity and left-hand, or σ_-, helicity) are exploited to form the optical fiber link **300**, and the unidirectionally spun fibers spans with right-hand, or σ_+, spinning helicity are alternated to the unidirectionally spun fibers spans with left-hand, or σ_-, spinning helicity, as schematically depicted in the drawing. Preferably, the unidirectional spin of the different fiber spans is constant in module.

Due to the fact that splicing together fibers with opposite helicity interrupts the transients of the PMD_c of a unidirectionally-spun fiber towards the unspun fiber value, the growth of the PMD_c of the optical fiber link **300** with the fiber link length, discussed in the introductory part of the present description, may be substantially reduced by the

above-described provision in the fiber link **300** of both type of fiber spans.

In principle, the lengths of the individual fiber spans ..., **305**$_{(k-1)}$, **305**$_k$, **305**$_{(k+1)}$, **305**$_{(k+2)}$, **305**$_{(k+3)}$ **305**$_{(k+4)}$, **305**$_{(k+5)}$, **305**$_{(k+6)}$, ..., might be whatsoever, but, as will be shown in the following, a careful choice of such lengths allows substantially reducing, or even eliminating, the effect of growth of the PMD_c with the fiber length (thereby, after a certain length, a practically constant PMD_c is achieved, lower than the one of the single-helicity, unidirectionally-spun fiber).

In particular, if the spin rates of the unidirectionally spun optical fibers with σ_+ helicity have substantially the same magnitude (modulus) as the spin rates of the unidirectionally spun optical fibers with σ_- helicity, the best results in terms of suppression of the PMD_c growth with the fiber link length are achieved by alternating, along the fiber link **300**, σ_+ and σ_- optical fiber spans of substantially same lengths. However, if the spin rates of the unidirectionally spun optical fibers with σ_+ helicity have a different magnitude (modulus) from the spin rates of the unidirectionally spun optical fibers with σ_- helicity, the lengths of the different σ_+ and σ_- optical fiber spans should depend on the respective spin rate absolute values.

Reference is now made to **Figures 3A** and **3B**, which are diagrams of the predicted variation of the PMD_c (in ordinate, unit $ps/km^{1/2}$) with the propagation distance (in abscissa, unit km) for the fiber link **300** for various lengths of the alternated fiber spans ..., **305**$_{(k-1)}$, **305**$_k$, **305**$_{(k+1)}$, **305**$_{(k+2)}$, **305**$_{(k+3)}$ **305**$_{(k+4)}$, **305**$_{(k+5)}$, **305**$_{(k+6)}$, ..., that make up the fiber link **300**, and for two different values of the fiber transient characteristic length L_T. The curves

have been derived in accordance with the teaching of Galtarossa *et al.*, "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003, pp. 1639-1641, relative to fibers with a single spin direction.

In particular, the diagram of **Figure 3A** relates to an optical fiber link **300** made up of alternated unidirectionally spun fiber spans of opposite helicity having a spinning period p = 0.25 m, a beat length L_B = 7 m, a correlation length L_F = 10 m, and consequently a transient characteristic length L_T = 32 km. The diagram of **Figure 3B** relates instead to a similar optical fiber link **300**, but having a spinning period p = 0.5 m, and thus featuring a transient characteristic length L_T = 8 km. In both cases, the evolution of the PMD_c with the propagation distance for alternated fiber spans ..., **$305_{(k-1)}$**, **305_k**, **$305_{(k+1)}$**, **$305_{(k+2)}$**, **$305_{(k+3)}$** **$305_{(k+4)}$**, **$305_{(k+5)}$**, **$305_{(k+6)}$**, ..., of length L_C equal to 5 km, 10 km, 20 km, 40 km and for an infinite span length (*i.e.* for a single helicity fiber) is shown.

It can be appreciated that, in both cases, when alternating optical fiber spans unidirectionally-spun with opposite helicity, the PMD_c after a transient attains a substantially constant value which is lower than that of the single-helicity unidirectionally spun fiber, and hence of the unspun fiber with the same beat length L_B and correlation length L_F. So, the typical behavior of the single-helicity, unidirectionally-spun fiber is substantially transformed in a behavior similar to that of an alternately spun fiber.

Comparing the two diagrams, it can also be appreciated that the smaller the value of the transient characteristic length L_T, the smaller the span length L_C necessary to achieve a same value of the PMD_c. It can be appreciated by

those skilled in the art that an optimum L_C value can always be evaluated from the link length, the maximum allowed number of spans, and the transient characteristic length.

From the two diagrams of **Figures 3A** and **3B** it can also be noted that, for a value of the beat length L_B = 7 m and a value of the fiber correlation length L_F = 10 m, a span length L_C substantially equal to the transient characteristic length L_T gives a PMD_c of about 0.04 ps/km$^{1/2}$, that is a value comparable to the one of the commercially available, alternately spun optical fibers.

The optical fiber spans ..., **$305_{(k-1)}$**, **305_k**, **$305_{(k+1)}$**, **$305_{(k+2)}$**, **$305_{(k+3)}$** **$305_{(k+4)}$**, **$305_{(k+5)}$**, **$305_{(k+6)}$**, ..., are typically cabled and the optical fiber link **300** previously described is therefore typically part of an optical cable line. As schematically shown in **Figure 4B** (the drawing is not in scale), an optical cable line **80** typically comprises a plurality of trunks of optical cable ..., **$805_{(k-1)}$**, **805_k**, **$805_{(k+1)}$**, **$805_{(k+2)}$**, **$805_{(k+3)}$**, **$805_{(k+4)}$**, ..., joined in series (*i.e.* concatenated) one to the other. Each cable trunk ..., **$805_{(k-1)}$**, **805_k**, **$805_{(k+1)}$**, **$805_{(k+2)}$**, **$805_{(k+3)}$**, **$805_{(k+4)}$**, ..., includes a respective optical fiber span ..., **$305_{(k-1)}$**, **305_k**, **$305_{(k+1)}$**, **$305_{(k+2)}$**, **$305_{(k+3)}$** **$305_{(k+4)}$**, **$305_{(k+5)}$**, **$305_{(k+6)}$**, ...

Each optical cable trunk ..., **$805_{(k-1)}$**, **805_k**, **$805_{(k+1)}$**, **$805_{(k+2)}$**, **$805_{(k+3)}$**, **$805_{(k+4)}$**, ..., has a typical length in the range from approximately 2 km to approximately 10 km.

With reference to **Figure 4A**, a cross-sectional view of an optical cable along the optical cable line **80** is shown; the optical cable typically comprises an optical core **81** containing a plurality of optical fibers **800**.

The optical core **81** may be of the "tight" type (as the one illustrated in the drawing), wherein the optical fibers **800** are embedded into a polymeric matrix disposed around a strength member **83**, or of the "loose" type, wherein the

fibers **800** are loosely housed within a single buffer tube centrally disposed within said cable, or within a plurality of buffer tubes stranded around a central strength member. Around the optical core **81**, the optical cable **80** is provided with reinforcing elements **84** and protective sheaths **85, 86**.

In "tight" type cabling, the contact between the fiber and the polymeric matrix prevents the twist imparted to the fibers to be released. In "loose" type cabling, the twist imparted on the fiber is not released, for typical cable lengths, due to friction between the fiber and the buffer tube, possibly enhanced by the presence of a jelly filler.

From a manufacturing viewpoint, the optical fiber link **300** can be obtained starting by producing two sets of unidirectionally spun optical fibers having opposite spinning helicity. The two sets of fibers are properly labeled, for example σ_+ and σ_-, so as to be able to distinguish fibers of one set from those of the other. Accordingly, the first set will be said to have a σ_+ helicity and the second set a σ_- helicity.

Preferably, in order to easy the task of alternating fiber spans with mutually opposite spinning helicity, the unidirectionally spun optical fiber with σ_+ helicity has substantially the same spin rate as the unidirectionally spun optical fiber with σ_- helicity.

Later on in the present description, an apparatus suitable to produce unidirectionally spun optical fibers will be described in detail, being intended that the way, and the apparatuses, by means of which the unidirectionally spun optical fibers are obtained are not limitative to the present invention.

Once two sets of fibers (σ_+ and σ_-) with opposite helicity have been produced, spans of predetermined length of these fibers are used in a cabling process of a known

type to produce an optical cable such as the one illustrated in **Figure 4A.**

A plurality of optical cable trunks is thus formed. These optical cable trunks are then connected one to another by known techniques, to form an optical cable transmission line such as the one illustrated in **Figure 4B.**

According to a first embodiment, each optical cable trunk may include, in its optical core, a certain number (for example, half of the total number) of fibers with a clockwise helicity and a certain number (for example, of half the total number) of fibers with a counter clockwise helicity. In this case, the optical cable trunks may be identical to each other.

According to a second embodiment, each optical cable trunks may include fibers of a single type, *i.e.* either of clockwise helicity or of counter-clockwise helicity. In this case, cable trunks including only σ_+ fibers and cable trunks including only σ_- fibers are produced.

Then the optical cable trunks are concatenated to each other to form the optical cable line **80**. To join together two optical cable trunks, a connecting device of a known type can be used, such as the optical fiber connecting assembly described in the United States patent US 5,778,131 or the compact joint Oasys$^{(R)}$ realized by Pirelli. In practice, the fibers exiting the ends of the two cable trunks are housed and routed in the connecting device, and then they may be spliced end-to-end by a fusion splicer of a know type, such as model FSM-40S/40S-B by Fujikura.

The optical fiber spans ..., **305**$_{(k-1)}$, **305**$_{(k+1)}$, **305**$_{(k+3)}$, **305**$_{(k+5)}$, ..., are so spliced to form the optical fiber link **300**. In particular, the optical fiber link **300** is formed by splicing alternately a fiber span ..., **305**$_{(k-1)}$, **305**$_{(k+1)}$, **305**$_{(k+3)}$, **305**$_{(k+5)}$, ..., from the right-handed (left-handed)

spun fiber set σ_+ (σ_-), with a fiber span ..., **305**$_k$, **305**$_{(k+2)}$, **305**$_{(k+4)}$, **305**$_{(k+6)}$, ..., from the left-handed (right-handed) spun fiber set σ_- (σ_+).

By properly choosing the spin rate of the σ_+ and σ_- optical fiber spans, in particular by making the transient characteristic length L_T suitably longer than the typical cable trunk length, the optical cable line obtained by joining optical cable trunks including optical fibers spans of opposite (σ_+ and σ_-) helicity has a low and substantially constant PMD_c.

If the optical cable trunks include optical fiber spans of a same helicity (either right-handed, *i.e.* σ_+, or left-handed, *i.e.* σ_-), the optical cable **80** is preferably made by alternating cable trunks including σ_+ fiber spans with cable trunks including σ_- optical fiber spans.

Alternatively, if the optical cable trunks include both σ_+ and σ_- optical fiber spans, the optical cable is preferably made by joining the different cable trunks in such a way that σ_+ fibers spans are spliced with σ_- fiber spans.

The Applicant has investigated the PMD statistical properties of an optical fiber link such as the link **300**.

It is known in the art that both unspun and alternately spun optical fibers present a Maxwellian statistical distribution of the DGD values. The Maxwellian distribution is characterized by a ratio between the average of the squared DGD, $\langle\Delta\tau^2\rangle$, and the square of the averaged DGD, $\langle\Delta\tau\rangle^2$, equal to:

$$r = \frac{\langle \Delta\tau^2 \rangle}{\langle \Delta\tau \rangle^2} = \frac{3\pi}{8} \approx 1.18$$

In **Figure 5** the numerically computed (predicted) ratio r is plotted as a function of the propagating length. The

optical fiber link parameters are the same as for the fiber of the diagram of **Figure 3A**, with a span length L_C = 5 km. The ratio r exhibits strong oscillations superimposed to a monotonous rise towards the asymptotic value, equal to 1.18. A value of r larger than 1.18 indicates a statistical dispersion of the DGD values distribution larger than that typical of the Maxwellian distribution. On the other side, a value of r smaller than 1.18 indicates that the DGD values are less dispersed than in the Maxwell case.

Figures 6A to **6F** are diagrams showing the statistical distribution of the DGD values at points (a) to (f) of **Figure 5**, respectively.

According to these results, an odd number of fiber spans joined together guarantees a Gaussian-like DGD statistical distribution narrower than the Maxwellian one, as shown in **Figures 6A-6D**, and correspondently in the points marked (a)-(d) in **Figure 5**. Here and in the following Figures, the dashed lines indicate the Maxwellian fit, and the solid lines the Gaussian fit. However, the narrowing of the distribution below the Maxwellian limit diminishes as the span number increases. On the other side, an even span number gives a DGD dispersion larger than, and asymptotically equal to, the Maxwellian distribution, as shown in **Figures 6E** and **6F**, and correspondently in the points marked as (e) and (f) in **Figure 5**.

The prediction of the DGD statistical distribution deviation mentioned in the introductory part of the present description is based on the following considerations. The statistical properties of the DGD are determined by the three stochastic Gauss-distributed components of the polarization dispersion vector Ωi, with i = 1, 2, 3, according to the formula (reported in a paper by A. Galtarossa *et al*, Optics Letters, Vol. 28, No. 18, September

2003):

$$DGD=\sqrt{\Omega_1^2+\Omega_2^2+\Omega_3^2}\ .$$

The PMD_c is the expectation value of the DGD statistical distribution, divided by the square root of the fiber length L.

In unidirectionally spun fibers, $\Omega_3{}^2$ behaves markedly differently from $\Omega_1{}^2$ and $\Omega_2{}^2$. For small z the DGD is mainly determined by the component $\Omega_3{}^2$, so that it tends to obey a Gauss-like distribution. As z increases, $\Omega_1{}^2$ and $\Omega_2{}^2$ catch-up, the three components tend to acquire the same statistical weight and the DGD becomes Maxwell-distributed.

In unidirectional fibers, the PMDc increase with z follows from the (asymptotically linear) increase with z of the averages $\langle\Omega_i{}^2(z)\rangle$, i=1,2,3. The Applicant has found that, by alternating spans of opposite helicity, these averages can be substantially reduced with respect to the single-helicity case, and that the shorter the span length, the stronger the reduction.

In the following, an apparatus and a method to produce unidirectionally spun optical fibers will be described in detail. It is understood that these apparatus and method are not limitative to the present invention, any other method, and apparatus, adapted to produce unidirectionally spun fibers being suitable.

With reference to **Figure 7**, a drawing tower **1** comprises a plurality of devices that are substantially aligned along a vertical drawing axis **2** (whence the term "tower"). The choice of a vertical direction in order to perform the main steps of the drawing process arises from the need to exploit the gravitational force so as to obtain, from a glass preform **3**, molten material from which an optical fiber **4** can be drawn.

In detail, the tower **1** comprises a furnace **6** for performing a controlled melting of a lower portion of the preform **3** (also known as preform neckdown), a feeding device **7** for supporting the preform **3** and feeding it into the furnace **6** from the above, a traction device **8** (at a lower end of the tower) for pulling the fiber **4** from the preform **3**, and a winding device **9** for storing the fiber **4** onto a reel **10**.

The furnace **6** may be of any type designed to produce a controlled melting of a preform. Examples of furnaces that can be used in the tower **1** are described in US 4,969,941 and US 5,114,338.

Preferably, a cooling device **12**, for example of a type having a cooling cavity designed to be passed through by a flow of cooling gas, is situated underneath the furnace **6** for cooling the fiber **4** leaving it. The cooling device **12** is arranged coaxially to the axis **2**, so that the fiber **4** leaving the furnace **6** can pass through it.

The tower **1** may also be provided with a tension-monitoring device **13** (for example of the type described in the United States patent US 5,316,562), and a diameter sensor **14** of a known type, preferably positioned between the furnace **6** and the cooling device **12**, for measuring the tension and the diameter of the fiber **4**, respectively.

Preferably, the tower **1** further comprises a first and a second coating devices **15**, **16** of a known type, positioned underneath the cooling device **12** in the vertical drawing direction and designed to deposit onto the fiber **4**, as it passes through, a first protective coating and, respectively, a second protective coating. Each coating device **15**, **16** comprises, in particular, a respective application unit **15a**, **16a** which is designed to apply onto fiber **4** a predefined quantity of resin, and a respective

curing unit **15b, 16b,** for example a UV-lamp oven, for curing the resin, thus providing a stable coating.

The traction device **8** may be of the single pulley or double pulley type. In the illustrated embodiment, the traction device **8** comprises a single motor-driven pulley (or "capstan") **18** that is designed to draw the fiber **4,** already coated, in the vertical drawing direction. The traction device **8** may be provided with an angular velocity sensor **19** that is designed to generate a signal indicating the angular velocity of the pulley **18** during its operation. The rotation speed of the pulley **18** and, therefore, the drawing speed of the fiber **4,** may be varied during the process, for example as a response to a diameter variation detected by detector **14.**

The tower **1** further comprises a spinning device **20,** positioned between the coating devices **15, 16** and the traction device **8,** for imparting a spin to the fiber **4** about its axis during drawing. For the purposes of the present description, the term "spin" denotes the ratio (disregarding a constant multiplication factor) between the angular velocity of rotation dq/dt of the optical fiber (where q is the angle of rotation of the optical fiber measured with respect to a fixed reference point) and the velocity of drawing. The spin defined in this way is typically measured in turns/m.

In one possible embodiment, illustrated in **Figure 8,** the spinning device **20** comprises a fixed support frame **21,** a DC motor **22** held by the frame **21** and a rotating member **23** held by the frame **21** and coupled to the motor **22** through a belt transmission **24.** The belt transmission comprises a first driving pulley **24a** rigidly coupled to the motor **22,** a second driving pulley **24b** rigidly coupled to the rotating member **23** and a belt **24c** connecting the first driving pulley

24a to the second driving pulley **24b**.

The rotating member **23** has a rotation axis corresponding to the axis **2**, *i.e.* to the axis of motion of the fiber **4** when entering and leaving the device **20**. The rotating member **23** comprises a first and a second sleeve-like end portion **23a, 23b** (respectively upper and lower), which are rotatably coupled to the support frame **21** by means of respective bearings **26** and which allows passage of the fiber there through. The second end portion **23b** is coupled with the second driving pulley **24b**.

The rotating member **23** comprises two arms **27a, 27b**, extending from the first end portion **23a** to the second end portion **23b**. The arms **27a, 27b** are substantially C-shaped, with a main straight central region parallel to the axis **2**, and are arranged symmetrically to each other with respect to the axis **2**. One of the two arms (the one indicated with **27b** in the drawing) carries a first, a second, and a third idle-mounted rotating pulley **28a, 28b, 28c** (from up to down in the drawing), substantially aligned in a direction parallel to the axis **2**. The three pulleys **28a, 28b, 28c** have the corresponding axes perpendicular to the axis **2** and are dimensioned so that the corresponding guiding grooves are substantially tangent to the axis **2**.

Referring back to **Figure 7**, the tower **1** may also comprise a tension-control device **30**, commonly known as "dancer", for adjusting the tension of the fiber **4** downstream the traction device **8**. The tension-control device **30** is designed to counterbalance any variations in tension of the fiber **4** between the pulley **18** and the winding device **9**. The tension-control device **30** may comprise, for example, a first and a second pulleys **30a, 30b** that are mounted idle and in a fixed position, and a third pulley **30c** which is free to move vertically, under the action of its own weight

and the tension of the fiber **4**. In practice, the pulley **30c** is raised if there is an undesirable increase in the tension of the fiber **4** and is lowered if there is an undesirable decrease in the tension of the fiber **4**, so as to keep the said tension substantially constant. The pulley **30c** may be provided with a vertical position sensor (not shown) that is designed to generate a signal indicating the vertical position of the pulley **30c** and therefore indicating the tension of the fiber **4**.

One or more pulleys **31** (or guiding members of other types) are advantageously provided for guiding the fiber **4** from the tension-control device **30** to the winding device **9**.

The winding device **9** comprises, in the illustrated embodiment, a first, a second, a third and a fourth guiding pulleys **36a, 36b, 36c, 36d,** held by a support member **37**, for guiding the fiber **4** onto the reel **10**. The winding device **9** further comprises a motorized device **33** for setting the reel **10** into rotation about its axis **34**. The motorized device **33** may also be suitable for reciprocating the reel **10** along the axis **34**, so as to allow helix winding of the fiber **4** thereon during drawing. Alternatively, the reel **10** may be axially fixed and the support member **37** (together with the pulleys **36a, 36b, 36c, 36d**) may be mounted on a motorized slide (not shown in the drawing) designed to reciprocate along an axis parallel to the reel axis **34**.

A twist apparatus **40** is advantageously used for de-twisting the fiber, *i.e.* for removing an undesired elastic twist stored in the fiber **4** when spun. This undesired twist, which tends to generate circular birefringence in the fiber, is produced during spinning of the fiber due to the presence of a fiber rotation constraint downstream the point of spinning.

The twist apparatus **40** may be used at the drawing

stage, in particular to de-twist the fiber **4** during winding thereof, or it may be used at a subsequent stage, for example during unwinding of the fiber **4** for re-spooling it on a bobbin suitable for shipment, as will be described in the following.

In practice, the twist apparatus **40** expressly applies to the fiber a twist (which will be called "de-twist") in a direction opposite that of the undesired elastic twist resulting from spinning. In the following, with "direction opposite to the direction of spin", referred to the direction of the de-twist, it will be intended the direction opposite to the direction of the twist resulting from spinning. The twist apparatus **40** may advantageously be integrated in the winding device **9** of the drawing tower **1.** In particular, the support member **37** and the pulleys **36a, 36b, 36c, 36d** may be part of the twist apparatus **40.** With reference to **Figure 9,** which illustrates one possible embodiment of the twist apparatus **40,** the support member **37** is a rotating member having the shape of a two-prongs fork and comprising a hollow spindle **41** and a first and a second arms **45, 46** extending from one end **41a** of the hollow spindle **41.** The spindle **41** is held coaxial to the axis **34** by a fixed frame **43** and is rotatably mounted thereon through bearings **44.** The spindle **41** is driven by a DC motor (not shown in the drawing) through a belt transmission (also not shown in the drawing). In use, the spindle **41** is designed to be passed through by the fiber **4** along the axis **34.**

The first and second arms **45, 46** are symmetrical to each other with respect to the axis **34** and have respective first portions **45a, 46a** rigidly connected to the spindle **41** and extending away from the axis **34** opposite to each other, and respective second portions **45b, 46b** parallel to the axis **34.** The first portions **45a, 46a** have a radial extension

greater than the radius of the reel **10**, and the second portions **45b**, **46b** have a length corresponding substantially to the length of the reel **10**. The reel **10** is located between the second portions **45b**, **46b** of the arms **45**, **46**.

The first pulley **36a** is positioned at the end of the spindle **41** facing the reel **10**, and is designed to deviate the fiber **4** to the first arm **45**. The second, third and fourth pulleys **36b**, **36c**, **36d** are positioned along the second portion **45b** of the first arm **45** and define a wavy path for the fiber **4** before it is fed to the reel **10**. The function of the third pulley **36c** (which is intermediate between the second pulley **36b** and the fourth pulley **36d**) is to avoid that the fiber **4** slips from pulleys **36b** and **36d**, and it might be dispensed for. The second arm **46** has only a balancing function and may carry three pulleys identical to pulleys **36b**, **36c**, **36d**, to have the same distribution of weights as the first arm **45**.

While the first, second and third pulleys **36a**, **36b**, **36c** preferably have the respective axes parallel to each other and perpendicular to the axis **34**, the fourth pulley **36d** is preferably tilted about an axis parallel to the axis **34**, of such an angle that it lies on a plane that is tangent to the fiber bobbin when the reel **10** is half filled.

The twist apparatus **40** preferably comprises a fiber position sensor **48** (for example a device model Keyence FS-V11P FU-35FA) positioned between the fourth pulley **36d** and the reel **10**, to provide a control signal for the alternate axial motion of the reel **10** (**Figure 9** shows, for example, two different positions of reel **10**) or of the support member **37**. In fact, as previously stated, a relative alternate motion shall be provided between the reel **10** and the support member **37** to allow helix winding of the fiber **4**.

The drawing tower **1** may further comprise a control unit

(not shown in the drawing), electrically connected to all the devices of the tower **1** to be controlled from the outside, and to all the sensors and the detectors present along the tower **1**.

The drawing tower **1** operates as follows.

The supporting device **7** feeds the preform **3** to the furnace, where a lower portion thereof (the neckdown) is melted. The fiber **4** drawn from the neckdown is pulled down from the traction device **8** and wound onto the reel **10** by the winding device **9**. Between the capstan **18** and the reel **10**, the tension-control device **30** regulates the tension of the fiber **4**.

As the fiber **4** is drawn, the sensors **13** and **14** monitor its tension and diameter. Such monitoring can be used to control the drawing process, for example by acting on the traction speed. When exiting the furnace **6**, the fiber **4** is cooled by the cooling device **12** and it is coated with two protective layers by the coating devices **15**, **16**.

The coated fiber **4** is then subjected to a unidirectional and substantially constant spin by the spinning device **20**. This is obtained by setting into rotation the rotating member **23** about the axis **2** at a constant speed. Each turn of the rotating member corresponds to one turn of the fiber **4** about its axis.

The spin rate is selected in such a way that the effects of the imperfections and irregularities of the fiber **4** are rendered substantially uniform in a length of the fiber **4** equal to at least the shortest typical beat length L_B. As a result, when signals are transmitted into the fiber, there is an exchange of power between the fundamental propagation modes and, therefore, a reduction of the PMD. Thus, it is possible to significantly reduce the negative effects caused by the asymmetric stress conditions and by

the imperfections of shape intrinsically present in the fiber **4**.

The Applicant has observed that the higher the spin rate, the better the performances of the fiber in terms of PMD. However, the higher the spin rate, the higher the elastic twist to be removed. The Applicant has verified that a spin rate between 1 and 8 turns/m allows reducing the PMD at acceptable values and at the same time introduces an amount of elastic twist that can be efficiently removed by the technique here described.

When spun, the fiber **4** transmits a corresponding torque upstream and downstream. Upstream, the torque is transmitted to the preform neckdown, where the plastic deformation of the melted glass "absorbs" the torque and "transforms" it into an intrinsic orientation of the birefringence axes of the fiber **4**. This intrinsic torsion is frozen into the fiber **4** as the fiber cools. Downstream, in the absence of any countermeasure, the torque would be transmitted as far as the reel **10**, where the fiber **4**, once wound, would keep a residual elastic twist. This elastic twist would introduce, if not controlled, an undesired circular birefringence in the fiber **4**.

In order to control the residual twist in the wound fiber **4**, the fiber **4** is de-twisted by the twist apparatus **40**. In practice, the rotating support member **37** is made to rotate about the axis **34**, in a sense opposite to the spinning sense (more precisely, as previously stated, in a sense opposite to that of the elastic twist generated by spinning). Each turn of the support member **37** about the axis **34** corresponds to one turn of the fiber **4** about its axis. The torque transmitted along the fiber **4** downstream the spinning device **20** is then at least reduced by the twist apparatus **40** before the fiber is wound onto the reel **10**.

In detail, the fiber **4**, after passing through the spindle **41**, is deviated by the first pulley **36a** towards the first arm **45**, is herein conveyed along the second portion **45b** with the required tension by the second and third pulleys **36b**, **36c**, and is finally fed to the reel **10** by the fourth pulley **36d**, in a direction substantially perpendicular to the axis **34**. While being rotated about the axis **34**, the reel **10** is also reciprocated along the axis **34**, so as to allow an helical winding of the fiber **4**.

The signal of the sensor **48** is used to control the speed of the alternate motion of the reel **10**, so that the fiber **4** is always made to pass in a predetermined position of the sensor **48**.

The Applicant has found that the PMD of the fiber **4** can be reduced to a minimum by imparting to the fiber, after it has been spun, a twist that not only removes the elastic twist generated by the spinning action, but also introduces a positive residual twist, *i.e.* a twist in the opposite sense. The Applicant has verified that a positive residual twist between 0 and 1.5 turns/m, preferably between 0.3 and 1 turns/m, allows reducing the PMD of spun fibers in a wide range of spin rates, at least up to 8 turns/m.

As previously stated, fiber de-twisting may be performed, instead of during the drawing process, at a stage subsequent to drawing, and may be associated with the operation of unwinding of the fiber **4** from reel **10**. For example, de-twisting may be performed during re-spooling of the fiber **4** onto a shipping spool to be shipped to a customer or during screening operations. Screening is a test operation, performed on an optical fiber to check the strength thereof, which comprises applying a predetermined longitudinal tension to the fiber **4** while it runs in a predetermined path, usually defined by pulleys.

As shown in **Figure 10**, the twist apparatus **40** may for example be used with the fiber **4** moving in the opposite direction, so as to perform fiber de-twisting while the fiber **4** is unwound. In particular, **Figure 10** illustrates a re-spooling assembly **70** comprising an unwinding device **9'** for unwinding the fiber **4** from the reel **10** and a further winding device **71**, including guiding pulleys **73**, for re-winding the fiber **4** onto a different reel **74**. The unwinding device **9'** substantially corresponds to winding device **9**, but operates in the opposite direction, to unwind the fiber **4**. In this case, the twist apparatus **40** is integrated in the unwinding device **9'** for de-twisting the fiber **4** as it is unwound from the reel **10**. The re-spooling assembly **70** may also comprise a screening device **72**, for example of the type described in US 5,076,104.

Figure 11 shows a different embodiment of the twist apparatus, indicated with reference numeral **50**. The twist apparatus **50** comprises a fixed frame **51** supporting the reel **10** along the axis **34**, and a rotating member **52** for twisting the fiber **4** as it is wound onto the reel **10** or unwound therefrom.

The rotating member **52** comprises a first and a second spindles **53**, **54**, supported by the frame **51** coaxially to the axis **34**, and a flexible arch member **55** connecting the two spindles **53**, **54** over the reel **10**, for the passage of the fiber **4**.

The fixed frame **51** comprises two external support members **56**, **57** and two internal support members **58**, **59** substantially aligned to each other along the axis **34**. The external support members **56**, **57** are cylindrical and the member **57** has an internal passage for the fiber **4**, along the axis **34**. The reel **10** is positioned between the internal support members **58**, **59** and it is supported thereby. The reel

10 is connected to a motor (not shown in the drawing) through a belt transmission **60**.

The spindles **53, 54** are opposite to each other with respect to the reel **10** and are connected to a same motor (different from that of the reel **10** and not shown in the drawing) through respective belt transmissions **62** (only one of which is illustrated), so that they can be rotated at a same speed. Each of the spindles **53, 54** is positioned between a corresponding external support member **56, 57** and a corresponding internal support member **58, 59**. The first spindle **53** carries internally a pulley **67** tangent to the axis **34** that allows the passage of the fiber **4** between the arch member **55** and a further pulley **69** tangent to the axis **34** carried by the internal support member **58**. The second spindle **54** carries internally a further pulley **68** tangent to the axis **34** allowing the passage of the fiber **4** between the external support member **57** and the arch member **55**. One or more further pulleys are provided for guiding the fiber to or from the reel **10**.

The flexible arch member **55** is preferably made of carbonium and forms a bridge over the reel **10** for the passage of the fiber **4** between the spindles **53, 54**. The arch member **55** may be provided with equidistant guiding U-bolts **61**, preferably made of ceramic and suitable to guide the fiber **4** along the arch member **55**. Alternatively, the arch member **55** may be provided with a guiding tube (not shown in the drawing), which offers the advantage of an easier set-up before the process start, allowing blowing of the fiber **4** from one end to the other of the arch member **55**.

The apparatus **50** is herein below described when operating for winding the fiber onto the reel **10**. Similarly to the apparatus **40**, the apparatus **50** may operate in the opposite direction to unwind the fiber **4** from the reel **10**,

for example in the re-spooling assembly **70** of **Figure 10**.

The fiber **4** is received through the member **57** and a first portion of the second spindle **54**, where it is deviated by the pulley **68** to the arch member **55**; the fiber **4** then runs over the entire arch member **55** and enters the first spindle **53**, where it is further deviated by the pulley **67** towards the internal support member **58** along the axis **34**; then, the fiber is further deviated by the pulley **69** and it is finally fed to the reel **10**.

The amount of twist to be applied to the optical fiber **4** for obtaining the desired amount of residual twist may be determined according to the following technique. In a first step, a test fiber section only subjected to spin is drawn. This test fiber section can be obtained, for example, by operating the drawing tower **1** of **Figure 7** with the twist apparatus **40** off (*i.e.* with the rotating member **37** in a staying condition) for a predetermined time. Then, the residual twist accumulated in the test fiber section wound on the reel **10** is measured in the following way.

The reel **10** is hanged on a support located at a predetermined height, for example at 2 m above ground. A corresponding length of fiber is unwound from the reel **10**, keeping it under a moderate tension. The upper end of the unwound fiber section is secured to the reel surface, while the free end is marked, for example with a small piece of tape (having a negligible weight) and it is left free to rotate. The measurement resolution depends on the length of the unwound fiber section. For a fiber length of 2 m, the number of turns can be measured with a resolution of about ¼ turns over 2 m, so that a resolution of about 0.125 turns/m can be obtained. If a higher resolution is required, a longer fiber can be used.

The Applicant has observed that the presence of the

fiber coating shall be taken into consideration for an accurate measurement of the residual twist due to spinning, since a residual twist is also accumulated in the fiber under the coating. Accordingly, after the residual twist of the coated fiber has been measured in the way previously described, the free end of the coated fiber is blocked and the coating is completely removed (using a conventional Miller stripper). The fiber is then left again free to rotate, and the additional rotation of the fiber is measured with the same resolution as above.

The operation is repeated over consecutive fiber sections of predetermined length, for example every 2 m, to reach a predetermined total measured length, for example between 20 and 60 m. The mean value is used to label the torsion value of the fiber.

After the residual twist due to spinning has been measured, the fiber drawing may be continued with the twist apparatus **40** turned on, suitably set to obtain the desired residual twist.

It is thus possible to obtain an optical fiber having a unidirectional intrinsic spin and an elastic twist equal to zero in module, or opposite to said spin and greater than zero in module.

The unidirectional intrinsic spin may be substantially constant or variable. In this second case, the spin function is preferably obtained by superposing a substantially constant function and a periodic function, and the twist is applied so as to vary the average value of the residual twist to the desired value. The elastic twist applied to the fiber is preferably comprised in module between 0 and about 1.5 turns/m, more preferably between about 0.3 and 1 turns/m.

Fibers with both helicities, clockwise and counter

clockwise, are produced by the process previously described by changing the rotation direction of the spinning device and of the twisting device. Once two sets of fibers (σ_+ and σ_-) with opposite helicity have been produced, spans of predetermined length of these fibers are used in a cabling process of a known type to produce an optical cable as previously described.

Although the present invention has been disclosed and described by way of some embodiments, it is apparent to those skilled in the art that several modifications to the described embodiments, as well as other embodiments of the present invention are possible without departing from the scope thereof as defined in the appended claims.

For example, although in the invention embodiment shown in **Figure 2** a strict alternation of unidirectionally spun fiber spans having mutually opposite spinning helicity is provided for, this is not to be construed as a limitation of the present invention, because an optical fiber link might also be produced by splicing unidirectionally spun optical fiber spans of opposite spinning helicity without necessarily respecting such a strict alternation.

Moreover, the optical fiber link may comprise one or more spans of unspun optical fibers or of alternately spun optical fibers, spliced to the unidirectionally spun fibers or arranged between two spans of unidirectionally spun fiber.

Experimental results

The Applicant has experimentally confirmed the predicted PMD_c increase in unidirectionally spun fibers.

To do this, two G.652 fibers have been drawn at a unidirectional spin rate of +3turns/m and -3turns/m, and completely de-twisted after the drawing process, in order to eliminate any residual elastic twist. The fibers have then

be loosely wound about a large diameter bobbin, and, to ensure that all the possible range of DGD values is explored, repeated DGD measurements have been performed, each time slightly perturbing the fiber deployment. In particular, the measure has been realized according to the Jones Matrix Eigenanalysis technique, using a PAT9200 polarimeter and a Tunics-Plus tunable laser. The wavelengths range from 1530 nm to 1620 nm has been scanned using a 10 nm step. Up to 1200 DGD values in one-hour time have been thus obtained. Circles and squares in **Figure 12** shows the measured PMDc as a function of z for the +3turns/m and -3turns/m fibers, respectively: it can be appreciated that the PMDc increases with the propagation distance, and converges to an asymptotic value, in agreement with the predictions reported in the afore-mentioned paper by A. Galtarossa *et al.* "Polarization mode dispersion properties of constantly spun randomly birefringent fibers", Optics Letters, vol 28 No.18, September 2003.

The Applicant has also experimentally confirmed the deviation of the DGD statistical distribution from the typical Maxwell distribution that was suggested in the same paper as affecting short spans of unidirectionally spun fibers. Referring to **Figures 13A** to **13D**, which show the measured DGD distributions of the +3turns/m fiber of **Figure 12** for z = 1,2,3, and 4 km respectively, (in the diagrams, the solid and the dashed lines represent the Maxwell and the Gauss fits, respectively; the x and y axis represent the DGD (in ps) and the counts), it can be appreciated that unidirectional spinning may indeed severely affect the DGD statistics. In particular, for short values of z the DGD distribution is well fitted by a very narrow Gauss curve, with a ratio R (ratio between the expectation value and the standard deviation) much higher than 2.4, which is the R

value of the Maxwell distribution. As z increases, the dispersion of the data around the expectation value increases (the ratio R decreases), and at the same time the distribution becomes more and more Maxwell-like.

The Applicant has experimentally confirmed the PMD growth reduction achievable by concatenating fiber spans of opposite helicity. Triangles in **Figure 12** report the experimentally measured PMD_c in fibers made by splicing alternated, 1-Km long spans of unidirectionally spun fiber of opposite helicity. In particular, samples of 1 Km of the aforementioned G.652 have been spliced together, having care to alternate the helicity. It can be appreciated that the PMDc stabilizes to a value of about 0.03 $ps/km^{1/2}$.

The PMDc measured at the splicing points exhibits an oscillating behavior with z, with the minima and the maxima corresponding to an even and to an odd number of spans, respectively. As indicated by the values of the ratio R (reported aside the triangles), the concatenation of an odd number of spans always gives a DGD dispersion greater than the concatenation of an even number. As z increases and the PMDc tends to stabilize, the DGD distribution becomes larger and Maxwell-shaped, and the value of R decreases down to 2.4.

Splicing together alternated fiber spans of 2 Km, the PMDc tends to a value of about 0.04 $ps/km^{1/2}$, while alternating spans of 3 Km does not provide a significant PMDc reduction with respect to the unidirectionally spun fiber. Thus, fiber span length equal to or lower than 1 Km seems to provide good results, at least in the fiber herein considered.

Numerical results

The Applicant has numerically verified all these experimental observations with a code based on the random

modulus model of the fiber birefringence (RMM) and is explained in P.K.A. Wai and C.R. Menyuk, "Polarization Mode Dispersion, Decorrelation, and Diffusion in Optical Fibers with Randomly Varying Birefringence", Journal of Lightwave Technology, Vol. 14, No. 2, February 1996. The simulations confirmed that the PMDc compensation holds for an arbitrary number of alternated spans, so that a fiber of any length with a controlled PMDc value can be manufactured. The shorter the spans length, the smaller the asymptotic PMDc value.

In **Figure 12** the dashed, dotted and solid lines represent the result of RMM numerical simulation of the unidirectional +3turns/m fiber, unidirectional -3turns/m fiber and concatenated alternating helicity (±3turns/m) link, respectively. The fit with experimental data is very good. The fibers parameters used for the simulations are the following:

- for the +3turns/m fiber and for the +3 turns/m spans in the alternated-helicity link: L_B=4m, L_F=2.34m;
- for the -3 turns/m fiber and for the -3 turns/m spans in the alternated-helicity link: L_B=5.6m, L_F=3.45m.